

Modelling the Italian household sector at the municipal scale: Micro-CHP, renewables and energy efficiency



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ABSTRACT

This study investigates the potential of energy efficiency, renewables, and micro-cogeneration to reduce household consumption in a medium Italian town and analyses the scope for municipal local policies. The study also investigates the effects of tourist flows on town's energy consumption by modelling energy scenarios for permanent and summer homes. Two long-term energy scenarios (to 2030) were modelled using the MarkAL-TIMES generator model: BAU (*business as usual*), which is the reference scenario, and EHS (*exemplary household sector*), which involves targets of penetration for renewables and micro-cogeneration. The analysis demonstrated the critical role of end-use energy efficiency in curbing residential consumption. Cogeneration and renewables (PV (photovoltaic) and solar thermal panels) were proven to be valuable solutions to reduce the energetic and environmental burden of the household sector (−20% in 2030). Because most of household energy demand is ascribable to space-heating or hot water production, this study finds that micro-CHP technologies with lower power-to-heat ratios (mainly, Stirling engines and microturbines) show a higher diffusion, as do solar thermal devices. The spread of micro-cogeneration implies a global reduction of primary energy but involves the internalisation of the primary energy, and consequently CO₂ emissions, previously consumed in a centralised power plant within the municipality boundaries.

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1. Introduction

1.1. Background

The household sector accounts for approximately 21% of the final energy consumption (or ~30 Mtoe (million ton equivalents of petroleum)) in Italy. This sector's exceedingly high energy inefficiency makes it one of the sectors with the greatest potential for improvement together with transport (32%, or ~44 Mtoe) [1]. In fact, whereas higher energy efficiency translates into higher profits through lower costs in the industrial and service sectors, the smaller savings involved in domestic systems have made homeowners much slower in implementing technological change, even more so where summer homes are concerned. Consumption inefficiency is principally related to buildings, domestic appliances and boilers; therefore, actions directed at improving the energy performance of buildings and the end-use of energy (both electrical

and thermal) have the potential to dramatically reduce consumption. The EU has set a goal of a 20% improvement in energy efficiency by 2020 [2]. Recent European directives seek to reduce residential consumption predominantly by a top-down approach through the promotion of end-use energy efficiency (e.g., appliances, boilers, light bulbs) and of manufacturer certifications. EU energy regulations, both current [3–7] and those yet to be adopted, have a critical role in ensuring that climate change and energy consumption objectives are pursued by trading off costs and benefits. Where domestic appliances are concerned, in addition to the product regulations affected by the implementation of Directive 92/75/EEC [3], voluntary agreements directed at achieving minimum energy efficiency thresholds have also been reached by the European Commission and manufacturers associations for various product types [1,8]. Before the approval of the relevant EU directives, energy efficiency in Italy was regulated by two ministerial decrees of 2004 [9,10] (and amendments thereof) stating the quantitative targets to be achieved to enhance end-use energy efficiency. The decrees charged the Italian Electrical Energy and Gas Authority with drawing up guidelines to enact the content of the decrees themselves. The result was an incentive mechanism known

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as “white” or “energy efficiency” certificates, which proved highly effective. Indeed, according to the same Authority, it has enabled savings of nearly 6 Mtoe in less than 5 years, corresponding to the residential consumption of ~ 1.6 million people or the output of a 700-MW thermoelectric plant, avoiding 16 million tons of greenhouse gas emissions [11]. Savings have been largest in domestic lighting through the replacement of traditional light bulbs with compact fluorescent ones. Significant savings have also come from more energy-efficient domestic appliances, air conditioning and heating systems as well as interventions in public lighting. The introduction of a FIT (feed-in tariff) as an incentive for installing PV (photovoltaic) plants has enhanced their diffusion in all sectors [12]. The Italian legislation has also acted on demand by promoting the adoption of more efficient technologies through fiscal incentives, e.g., tax benefits for building energy performance improvements and tax breaks for the purchase of high-efficiency appliances (both first installation and replacement/scrapping of a similar product). A FIT to stimulate thermal energy production by renewable energy and cogeneration is being examined.

1.2. Literature review and aims

Over the last few years, energy modelling for the residential sector has been a major research topic. Swan and Ugursal [13] reviewed the various techniques used for modelling energy consumption in this sector by identifying two distinct approaches: top-down and bottom-up. Wiesmann et al. [14] presented an econometric study modelling electricity consumption by the residential sector in Portugal, and Van Ruijven et al. [15] devised a bottom-up model for residential energy use in India starting from key dynamic energy use concepts in developing countries. Van Ruijven et al. [16] applied an automated model calibration procedure to analyse the calibration uncertainty of residential sector energy use. Daioglou et al. [17] modelled energy demand for several end-uses to analyse possible future developments of residential energy use in five developing world regions: India, China, South East Asia, South Africa and Brazil. Their results showed that climate policy can reduce residential energy emissions but may also slow the energy transition away from traditional fuels in low income classes. Wada et al. [18] studied the cost effectiveness of replacing current appliances in the residential sector with more efficient models and attempted to estimate the real impact of energy efficiency improvements on the reduction of greenhouse gas emissions through the deployment of energy-efficient technologies. Shimoda et al. [19] developed a model that simulates city-scale energy consumption in the residential sector by considering the diversity of household and building types and evaluated energy conservation policies for the residential sector. Ó Broin et al. [20] presented a bottom-up model to elucidate the impact of energy efficiency on the EU building stock up to 2050 under three different scenarios, finding that the EC (European Commission) 2020 goals for primary energy savings can be met by focussing on a combination of minimum efficiency construction standards, improved conversion efficiency standards for final energy to useful energy and a $\geq 2\%$ annual improvement in end-use efficiency applied at the useful energy level. Kelly [21] presented a “structural equation model” to calculate the magnitude and significance of explanatory variables on residential energy consumption, reporting that the main drivers behind residential energy consumption are the number of household occupants, floor area, household income, dwelling efficiency, household heating patterns and living room temperature. Kannan and Strachan [22] presented long-term decarbonisation scenarios for the UK residential sector using UK MarkAL and MarkAL-Macro energy–economic models. Gouveia et al. [23] presented a partial equilibrium TIMES model to assess technology options and final energy needs

for a range of parameter variations for each end-use in the Portuguese residential sector.

Our study differs from the existing literature in the original mix of technologies modelled (in particular, micro-CHP and solar thermal panels) and the energy demands analysed (both thermal and electrical for permanent and summer homes) on the municipal scale. This study investigates the potential of energy efficiency, renewable energies (solar thermal and PV) and micro CHP (combined heat and power) systems to reduce residential sector consumption in Pesaro, a medium-sized town in Marche (central Italy), and analyses the scope for municipal action in promoting their adoption through local policies. The energy scenarios were modelled using the linear-programming model generator MarkAL-TIMES. TIMES builds least-cost partial equilibrium development paths with perfect or myopic foresight. In this model, the energy economy involves suppliers and consumers of commodities, such as energy carriers, materials, energy services and emissions, and similar to most equilibrium models, it assumes competitive markets for all commodities. The result is a supply–demand equilibrium that maximises the net total surplus (i.e., the sum of producer and supplier surpluses). In TIMES, the modeller can define such constraints as technology penetration, taxes and the price of commodities [24]. A previous study by some researchers on our team [25] noted that analysis of the energy scenario on the municipal scale is an unusual application of the MarkAL and MarkAL-TIMES models and discussed the suitability of the latter to analysing municipal-scale scenarios. That paper [25] provides an overview of the effects of municipal-scale policies aimed at both the private and the public sector without delving into any particular sector. In a further paper, Comodi et al. [26] applied the MarkAL-TIMES model to assess the effect of low-carbon initiatives on public-sector energy consumption up to 2030. TIMES has previously been used to investigate household sector scenarios in Italy with a focus on electricity demand [27–29]. In contrast to these studies, our research applies the TIMES model generator to heat production and micro-CHP systems, including solar thermal plants, micro-CHP with Stirling engines, FCs (fuel cells), microturbines and ICEs (internal combustion engines). An additional aim of this study is to investigate the effect of tourist flows (concentrated in summer) on energy consumption by sketching scenarios for both permanent and summer homes. Because the analysis used national statistics and trends, the methodology and the considerations made here can, with due caution, be extended nationwide. In particular, two long-term energy scenarios (to 2030) were analysed: (i) BAU (*business as usual*) (BAU) and (ii) EHS (*exemplary household sector*). The former is a reference, “unconstrained” scenario, in which only current policies and those that are already scheduled to be adopted are considered, whereas the EHS scenario sets targets that can be pursued through municipal policies, highlighting the environmental benefits and costs resulting from their adoption.

This work is organised as follows. After the Introduction in Section 1, Section 2 outlines the Italian household sector. Section 3 describes the methodology used, technology database and scenario assumptions. Section 4 presents the results analysis, Section 5 the role of the micro-CHP systems and Section 6 the conclusions.

2. Energy consumption in the Italian residential sector

According to the Confederation of Italian Industry [1], energy consumption in Italy is divided almost equally among the industry, transport and residential sectors. Households account for $\sim 2/3$ of the final energy consumption by the residential sector, and the service industry accounts for the remaining $\sim 1/3$. Over the last few years, the demand for energy has increased substantially. Residential consumption in 2000–2005 rose by 16.2% overall, from

~26.5 to ~30.8 Mtoe/year, with the generation of thermal energy for heating accounting for ~80% and electricity consumption for only ~20%. Natural gas is the main energy vector (~62%), and appliances (excluding air conditioning) account for at least 58% of residential electricity consumption. Table 1 shows the national energy consumption of households by “end-use” and “energy vector” [1]. Table 2 reports the electrical energy consumption data divided among the main electrical appliances for 2004 [1].

3. Methodology

3.1. The household sector: the model of municipal energy demand

3.1.1. Permanent and summer homes energy demand

This study analyses household sector energy consumption in Pesaro, a coastal town in central Italy, where large numbers of tourists contribute to the local summer consumption of electricity, natural gas and vehicle fuels. The data indicate that tourists account for as much as 11% of the resident population in the summer [30]. The fraction of municipal energy consumption related to summer homes was calculated by dividing households into permanent and summer. Quantifying the incidence of summer homes on residential energy consumption and understanding how their energy consumption is likely to be affected by municipal cost minimisation and environmental policies is a special feature of this work.

The estimate of energy consumption for summer houses was carried out by cross-checking data coming from national census [31] and energy data provided by local utilities: the census provided the number of second homes; the utilities provided the number of contracts divided by typology and the total amount of their energy consumption. Data about typology of the contract is relevant because in Italy there are two types of contract for household natural gas users: “heating” tariff, typical contract for permanent homes, and “cooking and hot water” tariff, mainly used for summer homes where heating systems are not required. The same method is applied also with respect to household electricity contracts which explicitly indicate whether the household tariff is for a “main home” or a “second home”. Examination of the data regarding permanent and summer homes allowed the estimation of the electricity and natural gas consumption of summer households: in the summer, natural gas is used for hot water production and cooking, not for heating, resulting in distinctive patterns for the different household types by season, as shown in the tables below. Table 3 shows that despite the increasing diffusion of electronic equipment and devices, thermal energy, specifically natural gas, accounts for the bulk of consumption. Other fuels used for heating, such as LPG (liquefied petroleum gas), diesel fuel and biomass, are not included in the model due to their low usage and a lack of official figures. The energy consumption related to each application was obtained from the national statistics [1,8] and was calibrated to the municipal level. Table 4 reports the percent consumption of the

Table 2

National electricity consumption and shares of the main household electrical appliances (2004 data) [1].

Appliance	Consumption (GWh)	Share
Refrigerators	12,402	29%
Freezers	2890	7%
Washing machines	6631	15%
Dishwashers	3163	7%
Electrical ovens	2610	6%
Electrical boilers	9622	22%
Air conditioning	5813	13%
TOTAL	43,131	100%

energy commodities in 2004, the reference year, as a result of the calibration phase of the model. Because second homes are commonly used as summer homes or are rented out, they are usually equipped with older and less energy-efficient appliances; this was taken into account in the model.

3.1.2. Main drivers of the model

The model construction requires entering the appropriate drivers for the energy demand to be modelled. The thermal demand for heating was projected according to the trend of “population” and “total built area”. The base year population data and their projections to 2030 were obtained from official statistics [31]. The “total built area” was only available for 2004, the base year. Because the projection of the thermal energy demand to 2030 requires the rate of construction of new buildings, a rate of 0.8% was assumed, in line with the REEP (Regional Environmental and Energy Plan) of the Marche region [32]. Residential thermal energy consumption is closely related to building energy efficiency, which has recently become regulated in Italy. The average specific thermal energy demand related to existing buildings before 2006 was estimated to be 150 kWh/m²/year. The energy demand for space-heating was assumed to be 105 kWh/m²/year for buildings erected after 2006, 80 kWh/m²/year for those built after 2009, and 60 kWh/m²/year for those built after 2016. The combination of new building construction and building energy efficiency targets was implemented in the model as household thermal energy demand input, which was 13.3% lower in 2030 than in the reference year. The demand related to appliances was calculated based on Italian studies [27,28] providing market penetration estimates up to 2030. The overall energy demand by the households increased by 11% between 2005 and 2030. Finally, Table 5 shows the price of electrical energy and natural gas, the commodities considered in the study, from 2004 to 2030. The prices from 2011 onwards are IEA (International Energy Agency) projections [33,34].

3.2. Technology database

The energy consumption of various appliances depends on their diffusion and technical features. The diffusion data are obtained from the manufacturers’ market research data [8], and the technical specifications are taken from Ref. [35] for both current and future technologies. Distributed generation systems, such as micro-CHP

Table 1
Distribution of energy consumption by Italian households (2005) [1].

End-use	Fossil fuels and biomass ^a		Electricity		Total share
	Consumption (Mtoe)	Share	Consumption (Mtoe)	Share	
Heating ^a	21.25	85.0%	0.178	3.1%	69.69%
Cooking	1.44	5.8%	0.106	1.8%	5.03%
Hot water	2.3	9.2%	0.833	14.5%	10.19%
Lighting and sockets	0	0	4.639	80.6%	15.09%
Total	24.99	100.0%	5.756	100.0%	100.00%

^a Biomass boilers account for 1.2 Mtoe, or 4.8%.

Table 3

Residential energy consumption and share by vector (2004 data).

	Energy consumption (TJ)		Energy consumption (%)	
	Permanent homes	Summer homes	Permanent homes	Summer homes
Natural gas	1844.4	9.3	99.5	0.5
Electrical energy	350.5	18.4	95.0	5.0

Table 4

Shares of electricity and natural gas consumption by type of appliance in permanent and summer homes. (2004 data).

	Permanent homes		Summer homes	
	Electrical energy	Natural gas	Electrical energy	Natural gas
Hot water	14.5%	10.5%	26.0%	50.0%
Heating	1.2%	84.2%	0.0%	0.0%
Refrigerators	20.0%		32.0%	
Washing machines	9.4%		2.0%	
Dishwashers	6.7%		1.0%	
Freezers	6.0%		4.5%	
Entertainment	15.0%		11.0%	
Lighting	14.2%		5.0%	
Air conditioning	5.0%		8.0%	
Other thermal uses	5.0%	5.3%	6.0%	50.0%
Other electrical uses	3.0%		4.5%	

Table 5

Prices of electricity and natural gas entered in the model.

	2004	2010	2030
Electrical energy (€/kWh)	0.17	0.168	0.24
Natural gas (€/Nm ³)	0.582	0.582	1.697

systems and plants powered by renewable energy sources, were entered in the model because of their increasingly important role in meeting European environmental targets [4,6]. Because one of the aims of the work was to investigate their potential to reduce residential energy consumption, a special feature of this work is the construction of a database for micro-CHP, PV and solar thermal technologies.

3.2.1. Micro-cogeneration

Micro-CHP was only modelled for permanent homes because it was intended only for space-heating. The micro-cogeneration technologies entered in the model are as follows: Stirling engines [36–38], FCs [39–43], MGTs (micro gas turbines) [44,45] and ICEs [46]. These technologies have proven their capability to enhance the energy efficiency and reduce the environmental impact in the residential sector [47,48]. Based on the aforementioned references [36–48], the main techno-economic parameters assumed for each technology are listed in Table 6. In particular, the O&M costs were assumed to be fixed for Stirling engines and FCs and variable for MGTs and ICEs. The first two technologies were intended to meet the thermal energy requirements of apartments, while the second pair were intended for central heating (condominia). The CHPR (cogeneration ratio) is the ratio of thermal to electrical power. Because the policies to be implemented set a target for the thermal energy demand to be met with cogeneration, the investment cost is calculated per unit of thermal power produced (k€/MWt).

3.2.2. Solar thermal panels

The main techno-economic parameters selected for modelling solar thermal panels [49] are listed in Table 7, where the AF (availability factor), indicates the percent working hours over the

year (R, spring; S, summer; F, fall; W, winter), and “Eff” indicates the yearly average efficiency. Two panels with different efficiencies and costs are modelled; panel 1 is cheaper and less efficient but is suitable for summer homes, whereas panel 2 is suitable for permanent homes because it has higher efficiency and greater AF, even if this combination increases the cost.

3.2.3. Photovoltaic

In this work, PV system modelling assumes self-consumption of all of the electricity produced and the grid-connection of the plant [49–51]. Two PV panels are considered, differing only by their AF to take into account seasonality (permanent and summer homes). In fact, given the hypothesis of self-consumption of all of the energy produced, the two systems have the same AF in summer, and AF = 0 was entered for summer homes for the other months of the year. The AF data reflect the overall yearly production of the PVs in the town of Pesaro as suggested by the PVGIS tool developed by the Joint Research Centre of the European Commission [52,53]. The Italian FIT mechanism (“conto energia” [12]), and the electricity saved were entered as a negative operating cost. Table 8 reports the main techno-economic modelling data entered for PV technology; the O&M costs in the table do not include the FIT.

3.3. Scenario assumptions

The main goal of this study was to analyse the evolution of residential energy consumption in Pesaro Municipality based on two scenarios:

- BAU (business as usual) and
- EHS (exemplary household sector).

The BAU is a reference scenario, in which future energy consumption is hypothesised to depend on general demand trends and technology availability, without considering any specific policies except current energy policies and those scheduled to be enacted. Notably, it is not a trend scenario but an optimised scenario because the model works by assuming the minimisation of the total costs of all systems.

The EHS scenario shows the effects that the implementation of new energy policies could have on residential energy consumption and expenditure. The main constraint considered is the market penetration of new technologies such as micro-CHP systems, solar thermal and PV. Micro-CHP systems are not considered for summer homes because the low demand for hot water production and especially heating makes them unprofitable. The policy constraints and targets considered in the analysis are reported in Table 9.

4. Results and discussion

It should be noted that each scenario does not aim to predict future energy consumption values but rather to provide a description of consumption trends that can help evaluate the effect of different energy policies. While the BAU is a reference scenario, the EHS scenario allows the assessment of the effects of the constraints introduced in the model through comparison with the BAU

Table 6

Summary of the main techno-economic modelling parameters entered for micro-chp devices.

Technology	η_{tot} (%)	Investment cost (k€/MWt)	Fixed O&M costs (k€/MW)	Variable O&M cost (k€/TJ)	CHPR (%)	Commercially available since	Life
Stirling	0.81	300.00	3.333		5	2012	15
FC	0.81	500.00	3.333		4	2015	15
MGT	0.74	470.00		1.419	1.74	2006	20
ICE	0.72	500.00		3.700	1.25	2006	25

Table 7

Summary of the main techno-economic modelling parameters entered for solar thermal panels.

Technology	Year	AF-R	AF-S	AF-F	AF-W	Eff	Investment cost (k€/MW)	Start	Life
Solar thermal panel 1		0.06386	0.10948	0.05018	0.000	0.3	1580.00	2006	22
	2009						1343.00		
	2012						1030.00		
	2016						619.99		
Solar thermal panel 2		0.07451	0.12773	0.05854	0.000	0.35	2000.00	2010	25
	2014						1700.00		
	2020						1310.00		
	2024						790.00		

scenario. For this reason, the main outcome of scenario analysis is not an absolute value for each year but the difference between scenario curves, which highlights the effects of the policies (or new technologies) implemented. Another outcome of the scenario analysis is evaluation of the cost associated with the various energy policies, again in terms of differences in expenditure rather than absolute cost. In the following sub-sections, the results of the MarkAL-TIMES scenarios are reported.

4.1. BAU scenario

The BAU scenario modelled with TIMES is a result in itself and provides future consumption and technology mixtures according to cost minimisation criteria and scheduled constraints. It is not as a simple trend of the base year because it takes into account the constraints related to local or national policies that currently exist or are scheduled to be adopted. Table 10 shows the energy consumption by permanent and summer homes throughout the period under study.

Residential energy consumption is predominantly due to natural gas and declines consistently over the years, as most evident at the end of the study period (in 2030), when the decline is related to both the superior energy performance of buildings (see paragraph 3.1) and the penetration of new technologies (e.g., heat pumps, see Table 11). In particular, the consumption of both electrical energy and natural gas by summer homes is negligible compared with that of permanent homes. Similar electrical consumption trends, reaching a minimum in approximately 2020 and rising afterwards, are observed in permanent and summer homes alike. This is explained by the initial prevalence of the effect of technology replacement on the increase in energy demand, whereas from 2020, when replacement gives way to near-saturation and almost all appliances are high-efficiency ones, the effect of demand growth (e.g., electrical heat pumps) becomes prevalent again. In particular, due to the inputs entered in the model, replacement is faster over the first 15–20 years of the scenario, leading to market saturation for some technologies in its final period (as, for instance, in the case of refrigerators, Fig. 5, and lighting, Fig. 6). In practice, the model exploits all of the potential of the database of technologies before the end of the scenario in 2030. The contributions of some of the technologies are analysed below.

Fig. 1 reports the consumption features of the various building heating technologies up to 2030. In particular, consumption by electrical boilers is negligible, whereas the market share of heat pumps becomes significant in 2015–2020. The boilers for hot water production and space-heating installed in the base year are progressively replaced by newer boilers, and by 2015, they are almost completely substituted by new devices with higher efficiency (referred to as new boilers in Fig. 1). In the final year of the BAU scenario, there is a mix of the new technologies with a slight penetration of the heat pumps; the micro-CHP technologies did not enter the market. In summer homes, thermal energy demand is limited to hot water production because space-heating is not required during summer. Fig. 2 shows the hot water heating demand in summer homes over time and the technologies through which this demand is met; in particular, it is worth noting that solar thermal plants prove to be competitive and capable of significant market penetration, even in the BAU.

Tables 11 and 12 report the electricity consumption and its percentage of reduction per appliance in permanent and summer homes, respectively. The reduction of electrical energy consumption is higher in the former than the latter (−19.4% vs. −14.8%). The trend of household electricity consumption reflects the market trend of each electrical device and is influenced by several factors, such as availability, technology cost and efficiency and behavioural changes (penetration). The consumption for lighting and refrigerators decreases more in summer homes than in permanent ones. As anticipated in paragraph 3.1, summer homes were modelled as being equipped with older and less energy-efficient appliances; consequently, the effect of technology replacement is higher. The electrical consumption of both freezers and water heating declines in both permanent and summer homes.

In general, a comparison of Tables 11 and 12 reveals a decline in energy consumption for all appliances except air conditioners, dishwashers and cookers. The increased consumption related to air conditioning in both permanent and summer homes reflects the increasing demand for cooling devices, whose market penetration in 2005 was low. The increase is more marked in permanent homes due to the higher penetration of electrical heat pumps used to meet the heating demand in the cold season. Similar considerations apply to dishwashers. Fig. 3 shows that the increased electricity consumption due to rising market penetration (from 41% in 2005 to

Table 8

Summary of the main techno-economic modelling parameters entered for PV technology.

Technology	Year	AF-R	AF-S	AF-F	AF-W	EFF	Investment cost (k€/MW)	O&M cost (k€/MW)	Start	Life
PV (permanent homes)		0.2126	0.2126	0.2126	0.000	0.09	6000	1200.00	2006	20
	2014						3000	600.00		
	2022						2700	540.00		
PV (summer homes)		0.000	0.2126	0.000	0.000	0.09	6000	1200.00	2006	20
	2014						3000	600.000		
	2022						2700	540.00		

Table 9

Energy policies implemented in the BAU and the EHS scenarios.

Technology	BAU		EHS-policy constraints/targets	
	Permanent homes	Summer homes	Permanent homes	Summer homes
Building thermal energy requirement	Existing buildings: 150 kWh/sqm/year	Existing buildings: 150 kWh/sqm/year	Existing buildings: 150 kWh/sqm/year	Existing buildings: 150 kWh/sqm/year
	New buildings: 105 kWh/sqm/year (from 2006)	New buildings: 105 kWh/sqm/year (from 2006)	New buildings: 105 kWh/sqm/year (from 2006)	New buildings: 105 kWh/sqm/year (from 2006)
	80 kWh/sqm/year (from 2009)	80 kWh/sqm/year (from 2009)	80 kWh/sqm/year (from 2009)	80 kWh/sqm/year (from 2009)
	60 kWh/sqm/year (from 2016)	60 kWh/sqm/year (from 2016)	60 kWh/sqm/year (from 2016)	60 kWh/sqm/year (from 2016)
Electrical appliances	Minimum cost criterion	Minimum cost criterion	Minimum cost criterion	Minimum cost criterion
Thermal appliances	Minimum cost criterion	Minimum cost criterion	Minimum cost criterion	Minimum cost criterion
PV systems	Minimum cost criterion	Minimum cost criterion	Energy production equalling 10% of electricity consumption by 2030	Energy production equalling 5% of electrical energy consumption by 2030
Solar thermal plants	Minimum cost criterion	Minimum cost criterion	Energy production equalling 10% of thermal energy consumption for water heating by 2030	Energy production equalling 20% of thermal energy consumption for water heating by 2030
Micro-chp systems	Minimum cost criterion	Minimum cost criterion	Total thermal energy production equalling 20% of thermal energy consumption by 2030, of which: • 5% by MGT or ICE • 15% by Stirling or FC	none

~91% in 2030) is not offset by an increase in efficiency, as demonstrated by a constant decline in specific dishwasher consumption that plateaus in approximately 2025 because the model exploited all of the best available technology in the database before the end of the scenario in 2030. Nevertheless, Table 12 shows a reduction in the electricity consumption of dishwashers in summer homes (−38.9%) due to the lower market penetration set by the modeller. Electricity consumption for cooking initially decreases because of the increasing efficiency of domestic appliances, especially ovens, and then rises again due to a shift from gas to electrical cookers. In all three cases (i.e., air conditioning, dishwashers and cookers), energy efficiency acts by smoothing steep rises in consumption, but when the market penetration of electrical appliances approaches saturation, higher energy efficiency translates into a decline in energy consumption.

Fig. 4 shows that both total consumption and the specific energy consumption of washing machines plunge until 2015 and decline more slowly thereafter. This finding highlights the close interdependence between total and specific consumption, which can be explained as follows. Because washing machines are already quite widespread, the prevailing effect in this case is technology replacement, albeit with a narrowing in the efficiency difference over time. In this case, a comparison of Tables 11 and 12 shows a decreasing electricity consumption trend in both permanent and summer homes. Another interesting remark on Tables 11 and 12 is that refrigerators play a key role in household electricity consumption due to their high penetration, which exceeds 100% (>1 unit per dwelling), and their percent energy consumption incidence, ~14%. Consumption by refrigerators and deep freezers decreases consistently until 2015 and then plateaus because, as

Table 10

Consumption of electricity and natural gas by permanent and summer homes – BAU scenario.

		2005	2008	2012	2015	2020	2025	2030
Permanent homes	Electrical energy [TJ]	349.86	322.21	286.50	259.71	256.40	270.42	281.93
	Natural gas [TJ]	1844.34	1819.50	1726.38	1643.10	1547.36	1471.22	1395.57
Summer homes	Electrical energy [TJ]	18.43	16.99	15.10	13.69	14.04	15.02	15.71
	Natural gas [TJ]	9.23	10.75	13.48	15.27	15.46	15.21	14.93

Table 11

Electrical energy consumption in permanent homes – BAU scenario.

	Electrical energy consumption (TJ)							% Reduction
	2005	2008	2012	2015	2020	2025	2030	
Lighting	49.80	49.09	28.00	22.57	11.59	10.11	10.19	−79.5%
Washing machines	32.64	29.85	26.16	23.03	22.06	20.83	19.99	−38.8%
Dishwashers	23.48	24.49	27.52	27.72	30.57	33.60	37.42	59.4%
Cookers	17.58	22.45	21.39	14.18	17.62	16.92	10.06	−42.8%
Refrigerators	70.42	66.29	55.12	47.32	42.25	40.22	40.14	−43.0%
Freezers	21.01	17.95	11.04	11.74	11.00	10.04	9.16	−56.4%
Heating + air conditioning	21.64	23.37	29.95	35.88	49.65	64.44	78.24	261.6%
Hot water	50.19	24.80	20.40	8.47	0.00	0.00	0.00	−100.0%
Other uses	63.09	63.92	66.92	68.81	71.65	74.26	76.72	21.6%
TOTAL	349.86	322.21	286.50	259.71	256.40	270.42	281.93	−19.4%

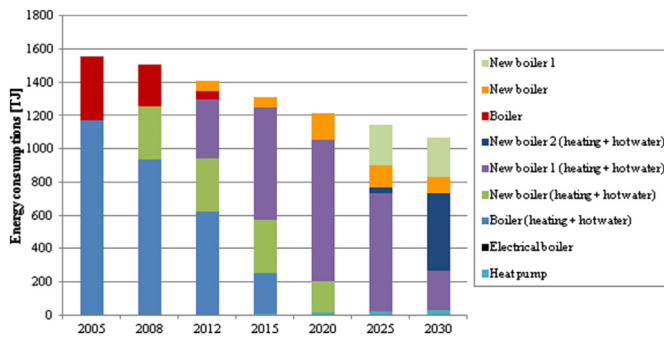


Fig. 1. Energy consumption trend for heating purposes – BAU scenario.

shown in Fig. 5, the technology share is variable until 2020, when only class “A+ new” and “A++” refrigerators remain. The figure reports the number of units and share of refrigerators based on energy efficiency class.

Consumption data for lighting are reported in Fig. 6, which shows the significant savings that can be achieved by replacing energy-inefficient incandescent and halogen light bulbs with fluorescent and, later, induction bulbs. In particular, although induction light bulbs are less efficient than the new fluorescent bulbs, their longer useful life makes the technology convenient in the medium-term, enhancing its market penetration.

4.2. EHS scenario

The EHS scenario implements the policies described in Table 9. Table 13 summarises the electrical and natural gas consumption by households by class (permanent or summer).

Given the aforementioned assumption that the energy produced by renewables and micro-CHP is entirely self-consumed, the consumption figures of Table 13 take into account the natural gas savings due to the installation of solar thermal panels (which produce 70.39 Tj of thermal energy in 2030) and the electricity produced by PV and micro-CHP systems (see Table 15). However, they do include the natural gas consumed to feed micro-CHP systems. A comparison of Tables 10 and 13 shows that energy consumption declines in the EHS but is higher than that in the BAU scenario in 2030, as though the energy policies entered into the model had a negative effect. The evaluation of CO₂ emissions in the BAU and EHS scenarios (Fig. 7) confirms the analysis. Both scenarios show a reduction of greenhouse gases in relation to the energy consumption reduction (23% and of 21%, respectively, compared with the base year). The higher consumption figures found in the EHS scenario are explained by the internalisation, after 2020, of part of the electrical energy production because a quota of the electricity that was previously imported from outside the municipality boundaries is now locally self-produced through micro-CHP.

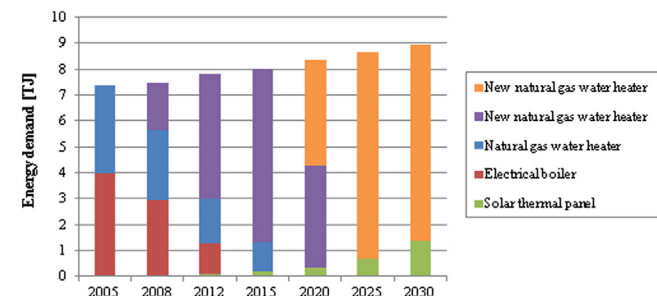


Fig. 2. Water heating demand and technology share in summer homes – BAU scenario.

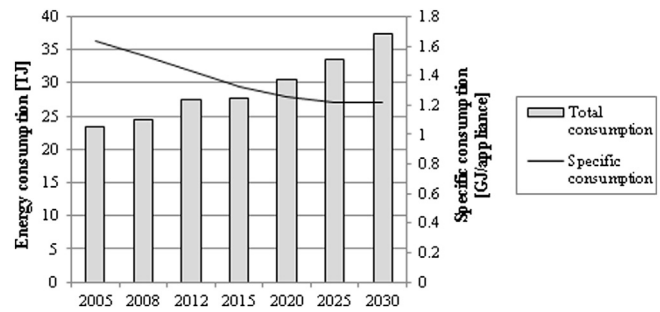


Fig. 3. Total and specific energy consumption of dishwashers – BAU scenario.

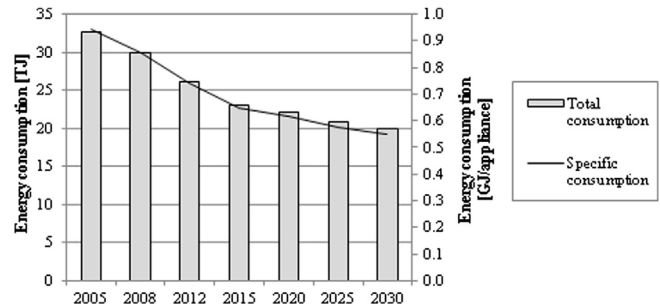


Fig. 4. Total and specific energy consumption of washing machines – BAU scenario.

The diffusion of micro-CHP technologies thus entails a greater use of primary energy within the municipality boundaries, as further discussed in the next section.

Where summer homes are concerned, the energy consumption is lower in the EHS scenario than in the BAU scenario due to both a greater penetration of renewable energy sources, such as solar thermal, and the absence of the internalisation effect caused by micro-CHP plants. The difference, expressed in terms of tCO₂, is clearly shown in Fig. 8. In particular, solar thermal technology is already present in the BAU scenario but becomes widespread in the EHS scenario, substantially reducing energy consumption. Table 14 shows the solar thermal energy produced for water heating in summer homes over the study period: the energy production in the EHS is more than four times that in the BAU, meaning that almost all of the hot water demand in the summer homes can be met using renewable energy sources.

Finally, Fig. 9 shows the disaggregated energy consumption figures for permanent homes in the EHS scenario. The trend shows that the energy consumption in permanent homes can be reduced by 20% in the final year of the scenario compared to the base year. In addition, the share of energy used to feed the micro-CHP devices becomes significantly higher than the direct consumption of electric energy.

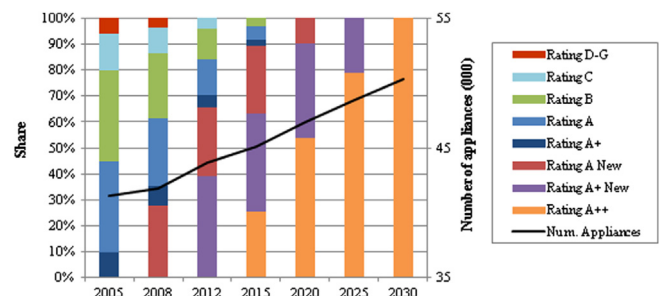


Fig. 5. Number and share distribution of refrigerators divided by energy efficiency class – BAU scenario.

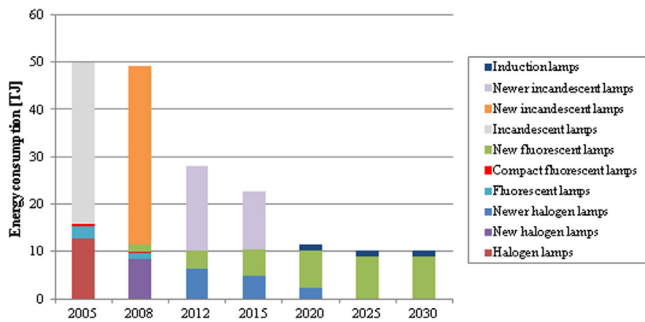


Fig. 6. Electrical energy consumption for domestic lighting – BAU scenario.

In terms of economic costs, a comparison of the BAU and EHS scenarios reveals ~291 M€ of added costs to enact the EHS scenario policies over the entire period considered. The share of the extra cost can be disaggregated by technology: the cost of achieving the policy targets is 25.78 M€ for solar thermal panels and 28.66 M€ for PV. The economic considerations regarding micro-CHP are discussed in Section 5.

5. Role of micro-CHP systems in the EHS scenario: environmental and economic considerations

Micro-CHP systems are highly energy-efficient devices that allow the contemporary production of electrical and useful thermal power starting from a single source of primary energy. The maximum energy efficiency of cogeneration systems is achieved when a concurrent demand of electrical and thermal energy exists [44,45]. For this reason, they are suitable for distributed generation applications and can strongly contribute to reducing the energy and environmental impact of the household sector [54]. The value of a CHP technology can be evaluated with the PES (primary energy saving) index, which compares the primary energy consumed by a cogenerator to produce a certain amount of electrical and thermal energy with that spent to produce the same amount of thermal and electrical energy separately (using a boiler and in a centralised power plant, respectively) [44,45,4]. A PES value of >0 indicates an advantage of CHP over separate production, corresponding to a

global primary energy savings. The PES index is calculated as follows:

$$PES = 1 - \frac{1}{\frac{\eta_{e_chp}}{\eta_{e_ref}} - \frac{\eta_{th_chp}}{\eta_{th_ref}}}$$

where η_{e_CHP} and η_{th_CHP} are the electrical and thermal efficiency of the cogenerator, respectively, while η_{e_ref} (assumed equal to 43%) and η_{th_ref} (assumed equal to 90%) are the reference efficiencies for separate production. In this work, calculation of the primary energy consumed by separate production of electricity assumed grid transmission losses of 6%.

Fig. 10 shows the trend of CO₂ emissions in the two scenarios; however, unlike Fig. 7, it allocates to the BAU (in which the CHP is not chosen by the model) the quota of emissions corresponding to the centralised production of the same amount of electricity produced in the EHS by micro-CHP. Considering the quota of electricity not produced outside municipality boundaries, the total emissions ascribable to the EHS scenario are lower than those of the BAU scenario, confirming the usefulness of promoting micro-CHP. The EHS scenario emissions would be lower than those of the BAU if the micro-CHP systems entering the market had higher electrical efficiency. However, because the policy constraints (see Table 9) focus on thermal energy, which represents the highest share of the energy consumption for the household sector (see Table 1), the TIMES model generator chooses the micro-CHP technologies with greater thermal efficiency (microturbines and Stirling engines). In fact, thermal energy production being equal, the demand is met by a smaller number of devices, reducing the capital outlay. The consequence of this choice is a reduction in the average CHP electrical efficiency (η_{e_CHP}), the parameter that most strongly affects the PES index. The results shown in Fig. 10 therefore confirm the overall advantage of micro-CHP in terms of CO₂ emissions. However, this advantage comes at the price of greater local consumption of fossil fuels, mainly natural gas, which compounds urban air pollution. Internalisation of energy production therefore attributes the responsibility for the additional environmental burden directly to the local government. Although distributed (co) generation is more easily accepted by communities than centralised plants (due to NIMBYism), the smaller scale requires careful planning of the technologies adopted. On the municipal scale, urban air quality generally has priority over overall energy efficiency; as a result, the adoption of micro-CHP may be affected by electrical efficiency or the PES index lesser strongly than by emissions levels. Although local emissions from micro-CHP systems have not been entered as a constraint in the model, the choice of microturbines made by the model for the EHS would meet low-emission requirements in any case because microturbines have lower CO and NO_x emission levels [45,55] than ICE.

With regard to the model, because micro-CHP policy targets are set as a share of the thermal energy demand, micro-CHP technologies are considered as alternatives to traditional boilers. The micro-CHP technologies included in the model are Stirling engine vs. FCs to replace boilers and microturbines vs. ICEs to replace centralised heating systems. The comparisons address the

Table 12
Electrical energy consumption in summer homes – BAU scenario.

	Electrical energy consumption (TJ)							
	2005	2008	2012	2015	2020	2025	2030	% Reduction
Lighting	0.92	0.90	0.61	0.48	0.20	0.16	0.16	–82.6%
Washing machines	0.37	0.33	0.30	0.27	0.27	0.27	0.26	–29.7%
Dishwashers	0.18	0.17	0.16	0.14	0.14	0.13	0.11	–38.9%
Cookers	1.11	1.07	1.21	1.19	1.05	1.22	1.17	5.4%
Refrigerators	2.07	1.74	1.34	1.03	0.97	1.00	1.01	–51.2%
Freezers	0.29	0.24	0.18	0.12	0.13	0.13	0.13	–55.2%
Air conditioning	1.47	1.71	2.25	2.54	3.06	3.61	4.07	176.9%
Hot water	4.80	3.49	1.39	0.02	0.00	0.00	0.00	–100.0%
Other uses	7.23	7.33	7.67	7.89	8.21	8.51	8.79	21.6%
TOTAL	18.43	16.99	15.10	13.69	14.04	15.02	15.71	–14.8%

Table 13
Electrical and natural gas consumption by permanent and summer homes – EHS scenario.

		2005	2008	2012	2015	2020	2025	2030
Permanent homes	Electrical energy (TJ)	349.86	322.21	281.64	242.67	220.12	207.95	194.22
	Natural gas (TJ)	1844.34	1819.58	1723.97	1635.97	1565.16	1506.09	1440.65
Summer homes	Electrical energy (TJ)	18.43	16.99	15.10	13.69	13.70	14.42	14.92
	Natural gas (TJ)	9.23	10.75	13.20	14.57	12.88	11.46	9.19

Table 14

Production of solar thermal energy for water heating in summer homes [TJ] – EHS scenario.

	2005	2008	2012	2015	2020	2025	2030
BAU	0	0.06	0.11	0.17	0.34	0.68	1.36
EHS	0	0.06	0.21	0.51	2.31	3.72	5.99

Table 15

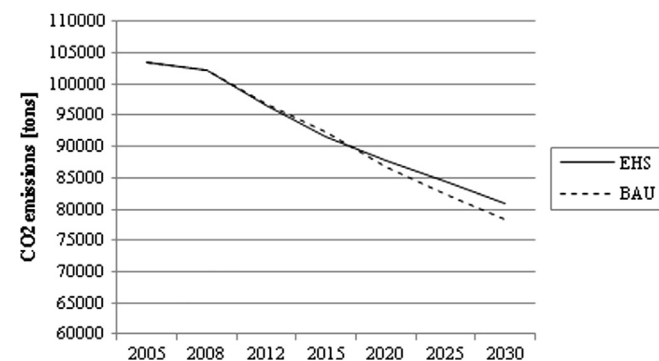
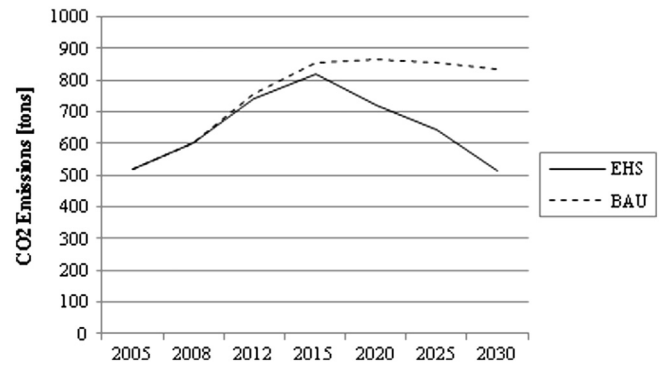
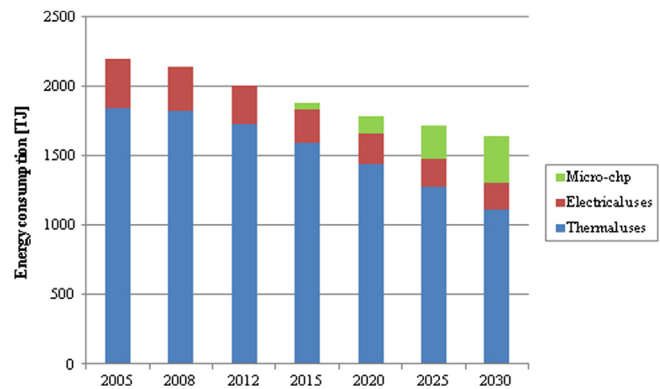
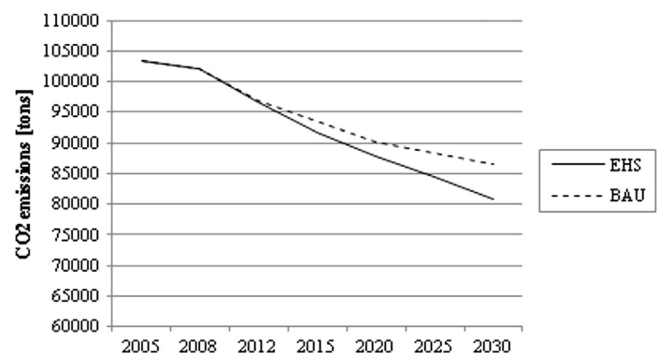
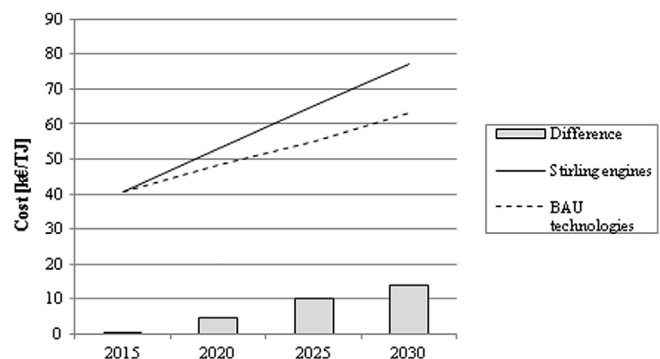
Electricity produced by the new technologies [TJ] – EHS scenario.

	2005	2008	2012	2015	2020	2025	2030
Micro turbine	0	0	0	4.83	12.47	21.17	29.13
Stirling engine	0	0	0	4.20	10.85	21.05	30.41
PV plant	0	0	4.86	8.02	12.97	20.28	28.19

annual production cost of the respective outputs: thermal energy for heating and electricity. The avoided cost of purchasing electricity (self-produced) is assigned a negative value (sale of electricity produced at the marginal cost) to refer the comparison to the sole cost of production of the thermal unit and compare micro-CHP technologies to the marginal cost of meeting the commodity “RHD (residential heating demand)”. As demonstrated by Figs. 11–14, the Stirling engine is the technology most closely approaching the marginal production cost of RHD (< difference). Fig. 11 shows that for the Stirling technology to be competitive, considering simultaneously the replacement dynamics and the improvement of RHD-related appliances, the cost of thermal unit production by Stirling micro-CHP plants should fall by ~0.20 €/GJ until 2015, by ~4.55 €/GJ until 2020, by ~10.17 €/GJ until 2025 and by ~14.06 €/GJ until 2030. The production costs (and differences) of the other micro-CHP technologies entered into the model, namely, FCs, microturbines and ICEs, are shown in Figs. 12–14, respectively.

Among the various cost items included in the analysis (investment, annual maintenance, other variables), fuel consumption is the most important. The hypothesis modelled herein considers a purchase price of natural gas for micro-CHP identical to that sustained for standard heating technologies (boilers). Where energy policies are concerned, the first issue to be addressed is therefore a reduction in the price of natural gas for micro-CHP (or an equivalent production incentive) to make the technologies more attractive.

The more concurrent the electrical and thermal energy demands are, the more competitive micro-CHP systems are. Because households need more thermal energy than electricity, microturbines and Stirling engines preferably enter the market due to their greater thermal efficiencies compared to ICEs and FCs,

**Fig. 7.** Comparison of CO₂ emissions in BAU and EHS scenario without internalisation.**Fig. 8.** Comparison of CO₂ emissions in BAU and EHS scenario in summer homes.**Fig. 9.** Energy consumption by permanent homes – EHS scenario.**Fig. 10.** Comparison of CO₂ emissions in BAU and EHS scenario with internalisation.**Fig. 11.** Comparison of the specific cost for thermal energy production using Stirling engine or BAU technologies.

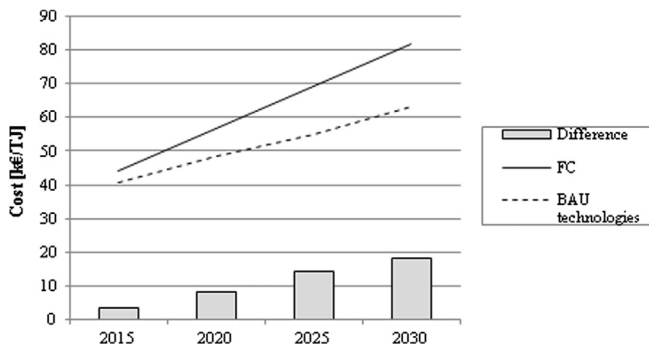


Fig. 12. Comparison of the specific cost for thermal energy production using FC or BAU technologies.

respectively. In fact, as explained above, the thermal energy demand being equal, a greater thermal efficiency entails fewer devices installed and consequently a lower initial outlay. When microturbines and ICEs are compared, maintenance costs also play an important role in the medium- to long-term. Both microturbines and Stirling engines are also able to meet a significant amount of the domestic electrical demand. Table 15 shows the electrical energy production obtained with the new technologies over the study period. These data show that micro-CHP systems can play an important role in the household production of electricity, even exceeding the amount produced by PV plants, which are already available on the market.

6. Conclusions

This paper presents two household sector energy scenarios modelled for a medium-sized municipality in central Italy. However, most findings may be extended to the national scale. One of the features of the study is that residential energy consumption was divided into that of permanent and summer households to account for the effect of summer tourism. Scenario analysis was carried out with MarkAL-TIMES, which proved to be an effective tool on the municipal scale. The main limitation of the model is that it assumes the final user to be virtuous and energy-aware; in fact, energy-efficient appliances and buildings are often managed inefficiently. Two scenarios are examined: BAU (business as usual) and EHS (exemplary household sector). The BAU is a reference scenario, where future energy consumption is hypothesised to depend on general demand trends and technology availability, without considering any specific policies except the current energy policies and those scheduled to be enacted. In contrast, the EHS scenario sets targets for energy efficiency or technology penetration. This

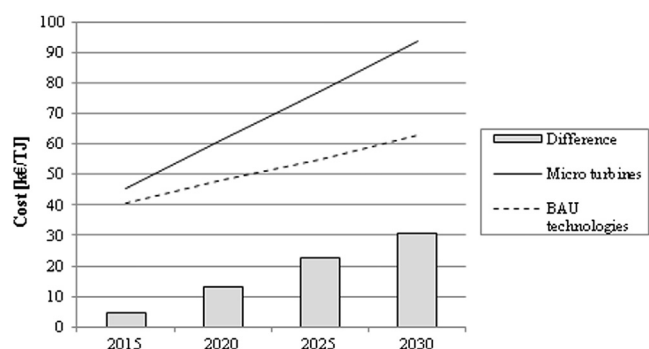


Fig. 13. Comparison of the specific cost for thermal energy production using micro-turbines or BAU technologies.

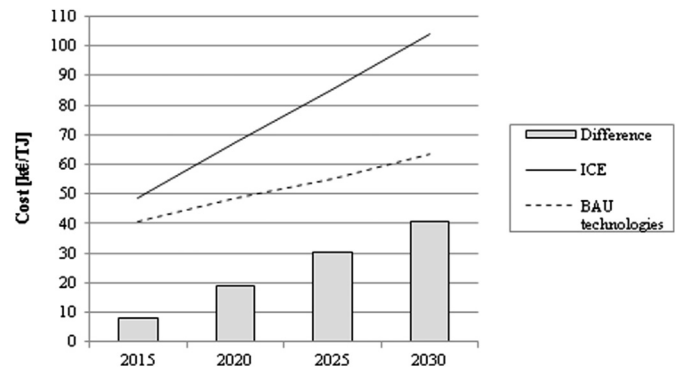


Fig. 14. Comparison of the specific cost for thermal energy production using ICE or BAU technologies.

paper demonstrates the critical role of final energy use efficiency in curbing residential energy consumption. For the BAU scenario in which energy efficiency is almost the predominant measure, the reduction was –23%. Greater energy efficiency has a different effect according to the market penetration of products: the greater efficiency of a widespread appliance (e.g., washing machines) translates into an overall reduction in energy consumption, whereas the greater efficiency of an appliance with growing market penetration (e.g., dishwashers) translates into a less steep rise in consumption. Solar thermal technology already enters the market in the BAU scenario (1.36 TJ) due to its high degree of competitiveness, particularly in summer homes; further incentives would likely boost its market penetration. Both scenarios showed a reduction in natural gas consumption (BAU, –21.8%; EHS, –24.3%) due to the greater energy efficiency of buildings and the greater penetration of heat pumps, which shifts energy consumption from natural gas to electrical energy.

One of the main findings of the study is the internalisation of energy production within municipality boundaries as a result of the installation of micro-CHP plants. A comparison of the 2030 and 2005 data shows that CO₂ emissions decreased in both the BAU and EHS scenarios. However, the reduction is greater in the former (~ –23%) than in the latter (~ –21%), which should be an “exemplary” scenario. This trend can be explained by the internalisation of the emissions, which are avoided in centralised plants outside municipal boundaries due to new local electricity production via micro-CHP, which entails higher local consumption of fossil fuels (natural gas). Nevertheless, taking into account the overall emissions avoided, the EHS scenario (~ –22%) is better than the BAU scenario (~ –17%). One consequence of this is that internalisation of energy production attributes greater responsibility to local governments, which in this scenario take on the environmental burden of some of the electricity consumed. The micro-CHP technologies entering the market were microturbines and Stirling engines because they better fit the demand of households in terms of the ratio between thermal and electrical energy.

One of the goals of the study was to investigate the role of the local government in promoting household sector energy efficiency through local policies. Energy efficiency and renewable energy incentives and targets are pursued at the national level; furthermore, because the Italian incentives mechanism does not allow them to be cumulated, any municipal initiative must take the national incentives framework into account. The municipal-level room for manoeuvring to boost energy efficiency and renewable energy in the household sector is therefore limited. The present data suggest the adoption of three local policies: i) information campaigns to enhance public awareness of the opportunities related to energy

efficiency and renewable energies (incentive mechanisms, lower energy bills, short payback times for the installation of energy-efficient products); ii) bureaucratic simplification for the installation of PV and solar thermal plants; and iii) local tax breaks, especially to boost micro-CHP. Indeed, because local taxes considerably affect the price of natural gas, the latter policy would be far easier to adopt in those cases in which the municipality is a shareholder in electrical or natural gas utilities.

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